

QUANTITATIVE ESD GUIDELINES FOR CHARGED SPACECRAFT DERIVED FROM THE PHYSICS OF DISCHARGES

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ABSTRACT

Quantitative guidelines are proposed for Electrostatic Discharge (ESD) pulse shape on charged spacecraft. The guidelines are based on existing ground test data, and on a physical description of the pulsed discharge process. The guidelines are designed to predict pulse shape for surface charging and internal charging on a wide variety of spacecraft structures. The pulses depend on the area of the sample, its capacitance to ground, and the strength of the electric field in the vacuum adjacent to the charged surface. By knowing the pulse shape, current vs. time, one can determine if nearby circuits are threatened by the pulse. The quantitative guidelines might be used to estimate the level of threat to an existing spacecraft, or to redesign a spacecraft to reduce its pulses to a known safe level. The experiments which provide the data and the physics that allow one to interpret the data will be discussed, culminating in examples of how to predict pulse shape/size. This method has been used, but not confirmed, on several spacecraft.

BACKGROUND

It would be helpful to have simple quantitative guidelines for the estimation of pulse magnitude and shape produced by high energy electron charging and spontaneous discharging of insulators. The estimate might allow one to design problem-free spacecraft, or to test for the rejection of the electrical pulses at sensitive nodes. These guidelines are proposed to elicit criticism and ideas from the community. Work on this problem is continuing.

The generic experiment that provides the data is depicted in Fig. 1. The irradiation of a planar insulator is simplest to discuss, but the concepts carry over to any insulator structure. Space radiation charges the sample with electrons that become trapped in the insulator. As the electrons accumulate, the free surface of the insulator achieves a significant negative voltage relative to surrounding grounded conductors. In nearly all experiments to date, the surface voltage of the insulator is of the order 1 to 50 kV, typically around 10 kV. The few existing measurements in space find similar voltages.

Resistor R in Fig. 1 represents both a test resistor (usually 50 ohms) and a sensitive circuit (any impedance) in the spacecraft. The occurrence of a spontaneous discharge of the insulator surface is accompanied by a rapid flow of electrons across the vacuum space to the chamber walls or to the sample substrate. This flow of current in the vacuum induces a current through resistor R that might threaten the circuit associated with the resistor.

In practice there are three R resistance regimes of interest: low impedance less than 100 ohms, medium impedance from 100 ohms to 10 k-ohms, and high impedance above 10 k-ohms. For the low impedance case, one determines the voltage across the resistor by multiplying the discharge currents experimentally measured in the 50 ohm test arrangement by the value of R. When R is less than 100 ohms, it has no effect on the current, I, for typical spacecraft insulator structures. When R lies between 100 ohms and 10 k-ohms, the voltage across R reduces the voltage in the vacuum space thereby reducing the discharge current flowing in the circuit. When R exceeds 10

k-ohms it may strongly reduce the current in the circuit because much of the original surface voltage is developed almost immediately across R. For cases of medium and high impedance the capacitance across R also becomes an important consideration.

The three impedance regions occur because the internal impedance of the discharge in the vacuum is typically between 200 ohms and 10 k-ohms for the more threatening discharges. Of course, small discharges with higher internal impedance do occur but they are not a threat, they are only a source of radio noise.

The physical sizes of the area being discharged and of the sensitive circuits are critical parameters. Lumped element modeling is not effective for the shortest pulses on typical circuit boards or wire bundles. The time scale of the vacuum arcs can be as short as 1 nanosecond or as long as one microsecond. The (transmission) line impedance of a circuit trace or cable wire is of the order of 100 ohms. For the shortest pulses into high impedance circuits with long wiring, the effective impedance, R, becomes the transmission line impedance of the wiring, typically 100 ohms.

This paper briefly discusses the important features of the vacuum discharge. The internal impedance of the discharge is usually a controlling factor. The initial voltage of the surface, its capacitance to ground, and its area combine with the internal impedance to control the form of the discharge pulse.

DISCHARGE PULSE PHYSICS

A typical discharge pulse is shown in Fig. 1. The vacuum current wave shape is usually triangular, although the rising and falling sides only sometimes have similar "slopes". When the surface area of the insulator is highly elongated the pulse will be flat topped. The rise and fall rates will be controlled by, among other things, the smallest dimension of the surface. The total length of the flat top will depend on the difference between the small dimension and the large dimension. A nearly square or circular sample will produce a narrow-peaked triangular pulse.

The important physics of the discharge can be qualitatively described. A surface and/or bulk discharge tree spontaneously forms in the insulator and generates gas of the insulator material. The gas is slightly ionized and rapidly spreads into the vacuum. The pulse occurs when a Thompson discharge forms in the gas under the stress of the high electric field between the insulator surface and the grounded walls. The initial leading edge of the pulse may be due to electrons alone moving from the insulator to the walls. But the vast majority of current is carried by the gas discharge which generates many more free electrons and ions. The current continues to rise as more gas evolves, becomes ionized, and spreads to discharge more of the surface.

Initially, the increasing accumulation of gas in the vacuum produces an increasing amount of current. The production of gas is initially controlled by the insulator discharge process itself. Ions and electrons from the initial gas bombard surfaces and liberate more gas. Experience indicates that the amount of gas is sufficient to carry hundreds of amperes, and at least to 100 amperes the gas is not a limiting factor. Eventually the surface becomes more than half discharged, and despite increasing amounts of gas, the electric field is so reduced that the current in the gas discharge falls rapidly.

The following parameters take part in controlling the current in the pulse:

1. Time-integrated current (charge) is controlled by surface capacitance and voltage.

2. Current slew rate, dI/dt , is controlled by electric field in the vacuum near the insulator surface, and by rate of change of gas pressure.
3. Peak current is controlled by slew rate and the smaller linear dimension of the surface.
4. The fact that this is a diffuse gas discharge causes the internal impedance of the discharge to nearly always exceed 100 ohms. The external circuit modifies the current only when its complex impedance is comparable or larger than the discharge impedance, thereby modifying the electric field in the vacuum.

The primary parameter, slew rate, is set by the gas ionization process. For the worst pulses, slew rate has the following dependence on electric field:

1. At $E=1E3$ V/m the slew rate is $1E8$ A/sec.
2. At $E=5E4$ V/m the slew rate is $1E9$ A/sec.
3. At $E=1E6$ V/m the slew rate is $1E10$ A/sec.

These data are averages over many pulses and are not precise. Accumulation of more data will be helpful. Dependence on sample material and vacuum dimensions are not yet determined but may be interesting when and if a sufficient variety of materials are investigated.

ESTIMATION OF PULSE SIZE

One can assume for square or circular samples that the pulses have the shape shown in Fig. 1. Half of the pulse is linearly rising, the other half is linearly falling at a similar slew rate. Proceed as follows. Define S = slew rate, C = surface capacitance to ground, V = surface voltage to ground, $Q=CV$, Dt = full pulse width, and I_p = peak current. It is easy to derive that

1. Dt = square root of $(4Q/S)$,
2. $I_p = S Dt/2$.

This result is a reasonable facsimile of the data in the literature and unpublished test data from many sources when the resistor R is less than 100 ohms and sample surface voltage exceeds 1 kV. For large resistance R one subtracts the voltage drop across R from the surface voltage in order to correctly estimate electric field in the vacuum. As the vacuum electric field drops when the resistor voltage rises, the slew rate will drop, and thereby the peak current will not rise as large. The case of large R is not considered important at this time in the development of the guideline. If R is large, a dangerous peak voltage greatly exceeding 100 V is developed across the circuits, and for modern integrated technology one need not proceed any further with analysis. Instead, the pulse must be prevented.

Application of this procedure finds the following general trends. For a spacecraft surface discharge to space, the threat (peak current) is small. For discharging of surface elements of spacecraft to other surface elements, the threat is moderate. For discharging of antenna insulators to antenna cables, the threat is large. For discharging inside electronic boxes, the threat is large. Inside cable bundles, a floating conductor is a large threat while typical wires are a moderate threat.

REFERENCES

- L. Levy, et al, IEEE Trans. Nuc. Sci. 38, 1635 (1991).
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- E. P. Wenaas, et al, IEEE Trans. Nuc. Sci. 26, 5152 (1979).
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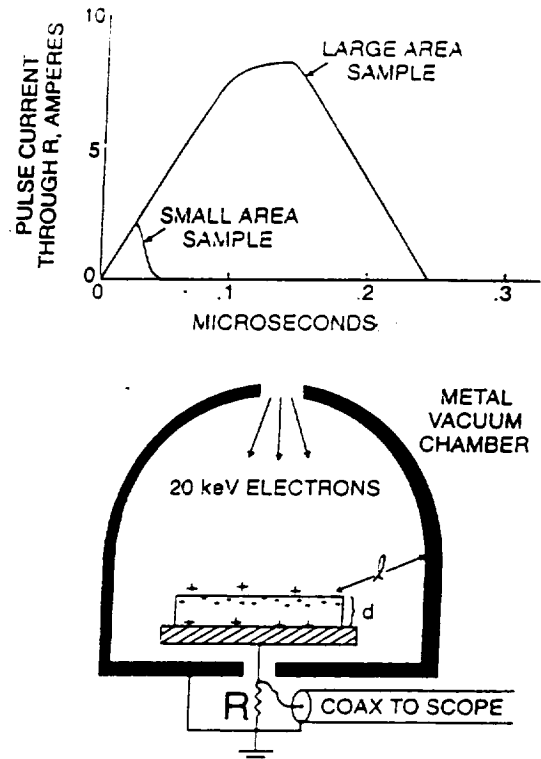


Figure 1. Typical Pulse and Experimental Apparatus. Dimension L has varied from 5 cm to over 1 meter in the various apparatus reported in the literature. Sample areas vary from a sq. cm. to a sq. meter. R has varied from less than 1 ohm to 50 ohms. The pulse shown has a low slew rate typical of low voltage (1 kV) in a large chamber (1 m).

In practice there are three R resistance regimes of interest: low impedance less than 100 ohms, medium impedance from 100 ohms to 10 k-ohms, and high impedance above 10 k-ohms. For the low impedance case, one determines the voltage across the resistor by multiplying the discharge currents experimentally measured in the 50 ohm test arrangement by the value of R. When R is less than 100 ohms, it has no effect on the current, I, for typical spacecraft insulator structures. When R lies between 100 ohms and 10 k-ohms, the voltage across R reduces the voltage in the

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To derive these equations one assumes that the pulse shape has equal rise time and fall time. Inspection of the results of many experiments indicates that this is not true. The rise time and fall times may differ by a factor of two or three. As a result of this, the value of I_p might vary from the estimated value by 50%. For most applications, I_p is a critical parameter which determines whether the spacecraft suffers a problem. Addition of 50% to the estimated I_p would be a necessary safety margin.

In some cases the slew rate is equally important. For example, the slew rate helps to control the extent in frequency space occupied by the pulse. If one wanted to filter the signal, then the pulses with diverse slew rates would be hardest to filter. Further review may delineate the range of slew rates experienced in testing.

Application of this procedure finds the following general trends. For a spacecraft surface discharge to space, the threat (peak current) is small. For discharging of surface elements of spacecraft to other surface elements, the threat is moderate. For discharging of antenna insulators to antenna cables, the threat is large. For discharging inside electronic boxes, the threat is large. Inside cable bundles, a floating conductor is a large threat while typical wires are a moderate threat.

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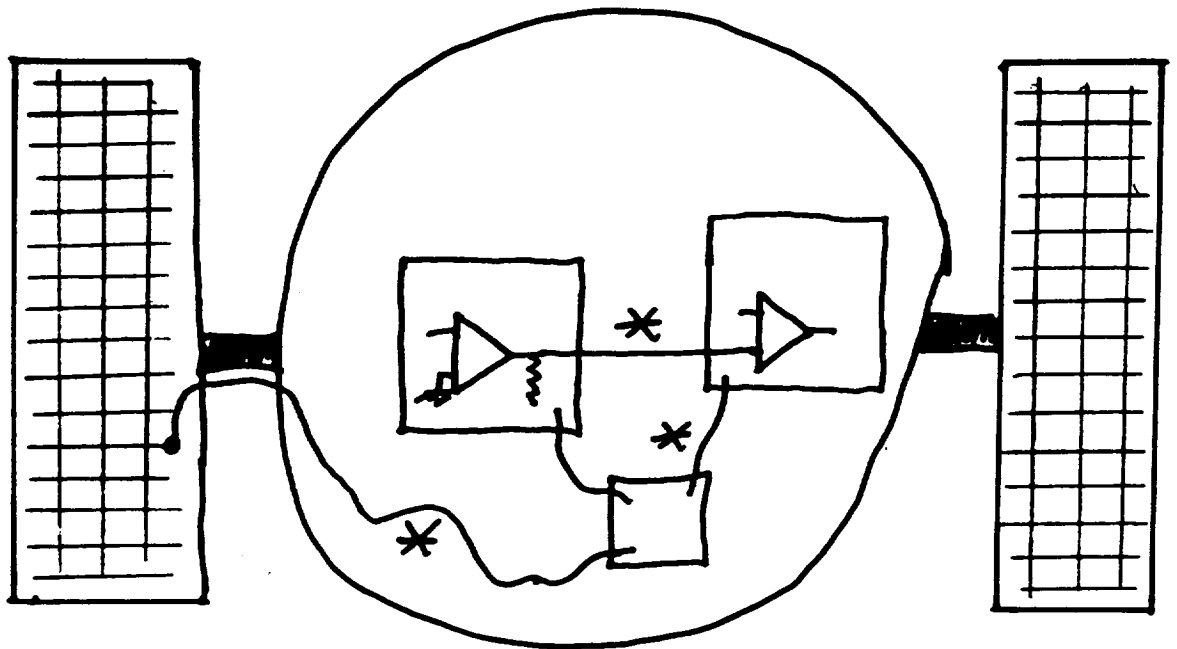
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Presented at the 1999 HEART Conference, Monterey CA, 12 March 1999.

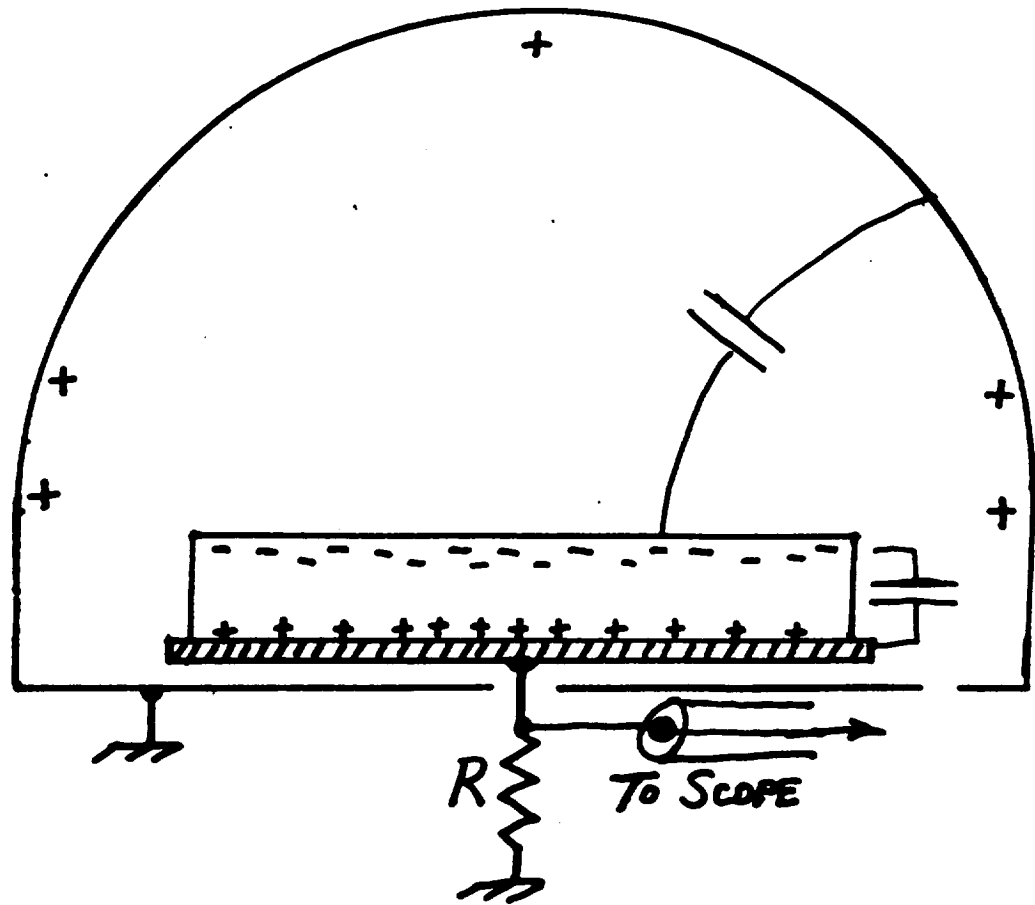
This work was sponsored in part by the NASA MSFC SEE Program

THE GENERIC PROBLEM

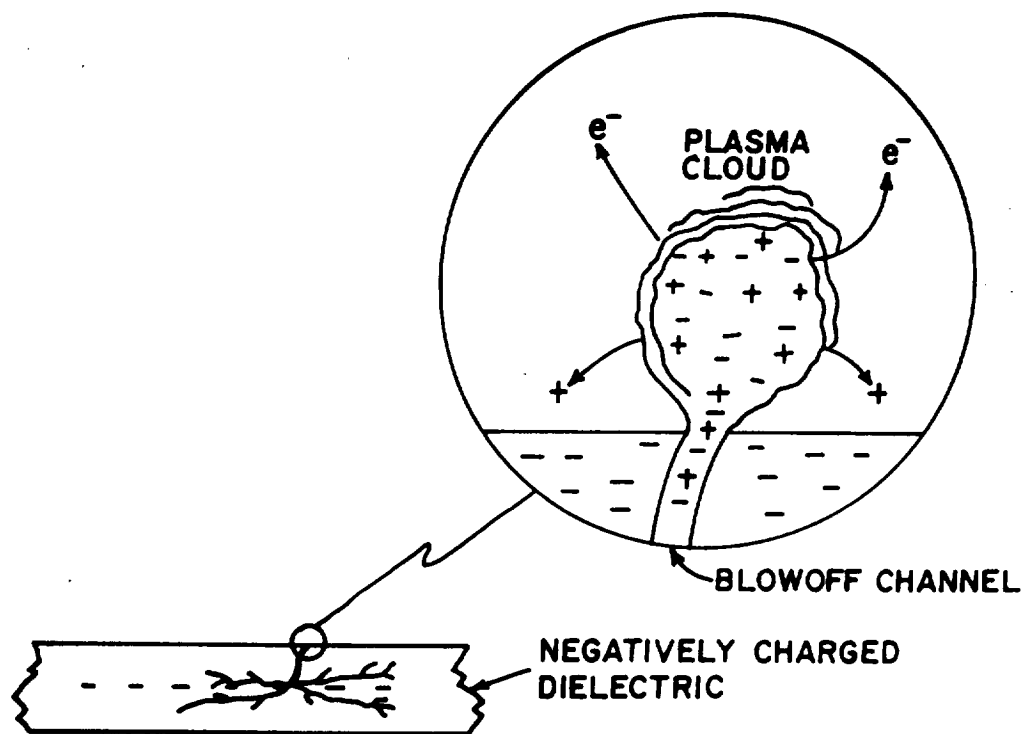


* SIGNAL ON THE LINE IS ?

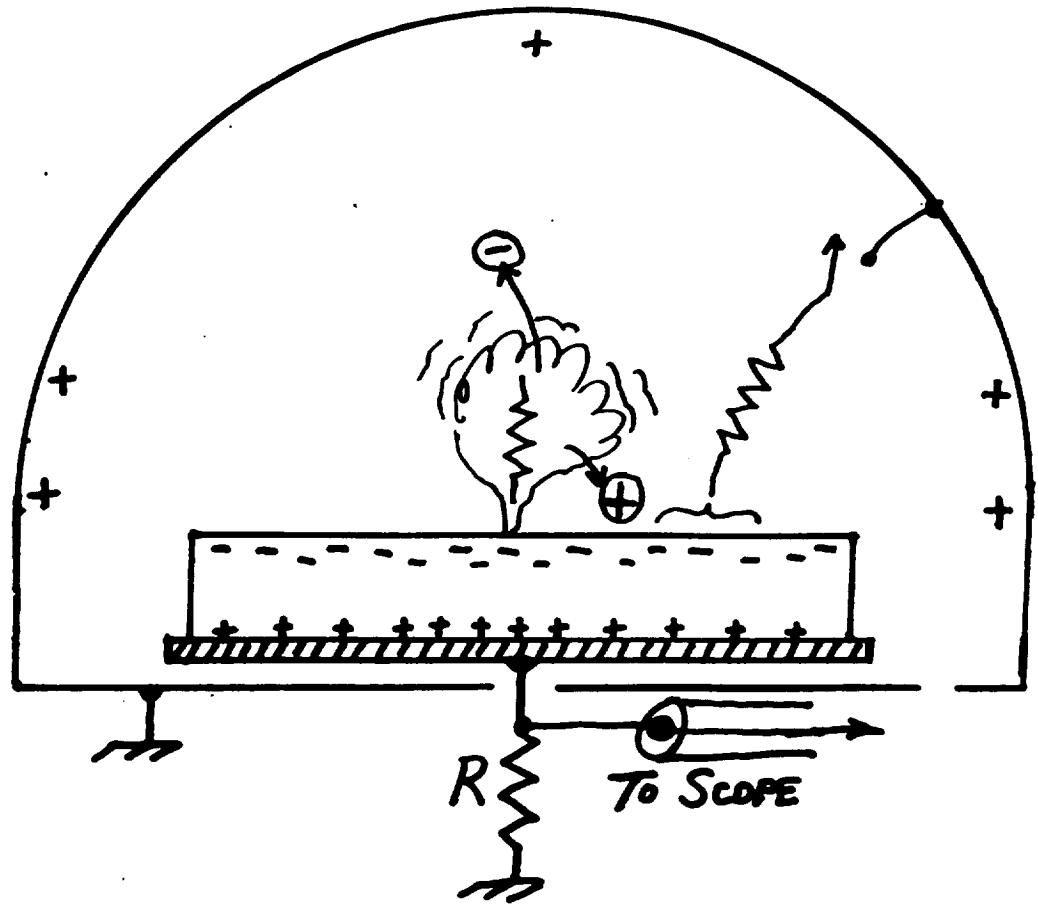
INITIAL CONDITION



ELECTRONS STUCK IN INSULATORS. HOLES
AS IMAGE CHARGE IN METAL. HOLES
ARE DISTRIBUTED ACCORDING TO CAPACITANCE.

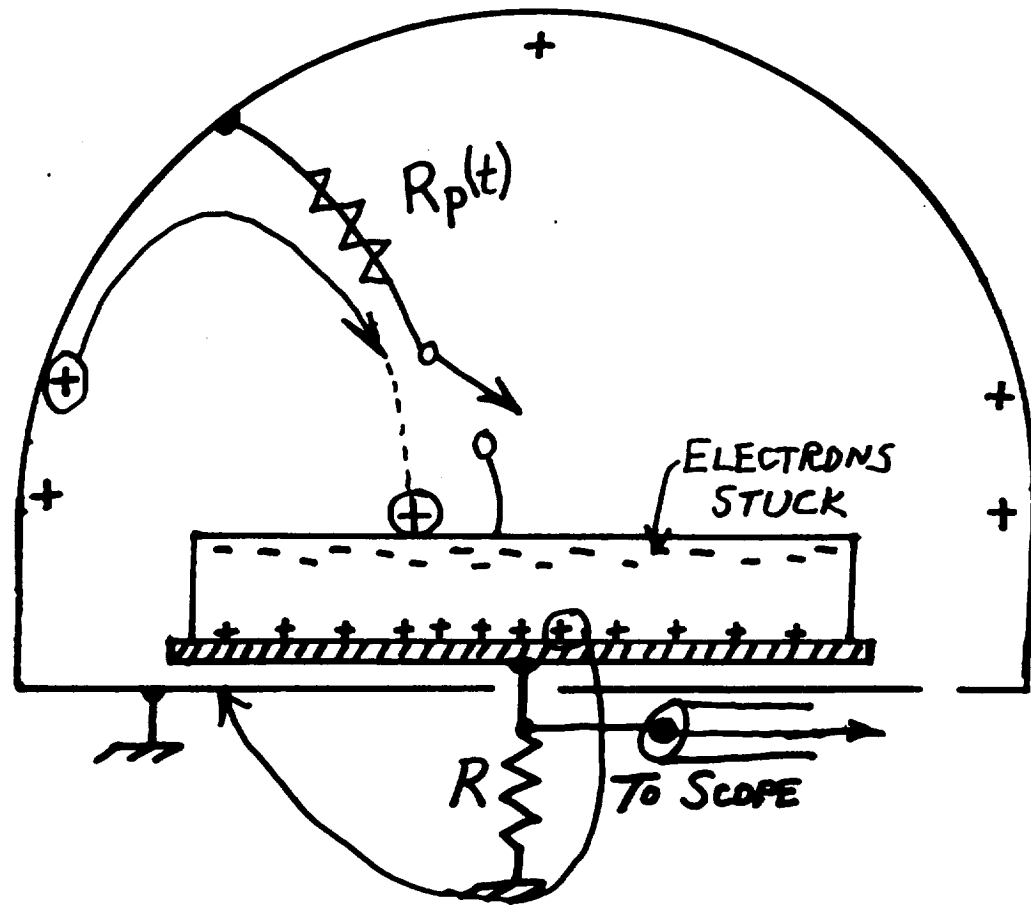


WHAT DOES THE PLASMA CLOUD DO?



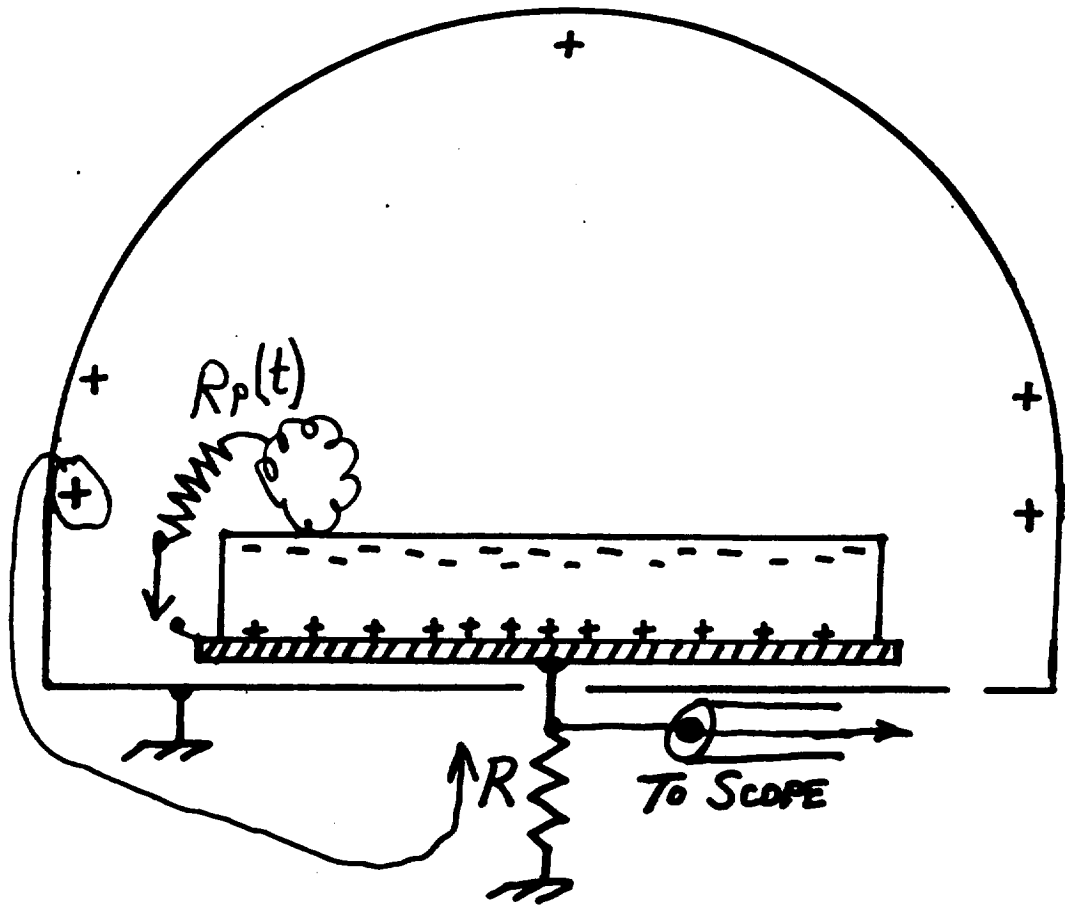
PLASMA CLOUD "CONDUCTS" I
HOLES, + IONS MOVE TOWARD STUKE e^-

WHEN THE PLASMA FORMS THE CONDUCTION
WHERE DO THE CURRENTS FLOW?



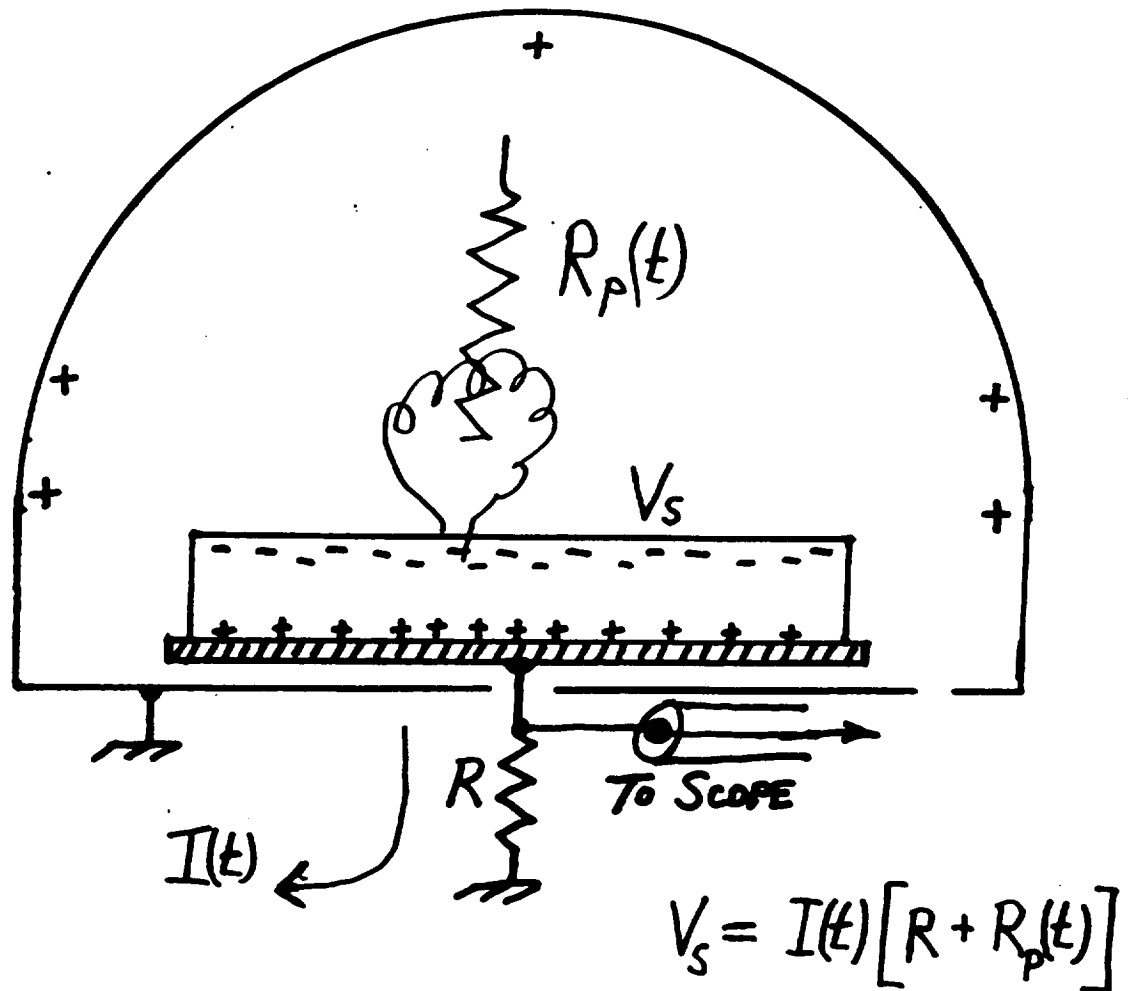
ANSWER: THE HOLES MOVE CLOSER
TO THE STUCK ELECTRONS,
POSITIVE SCOPE TRACE.

WHAT IF PLASMA CONNECTS
TO THE BACK PLANE ?



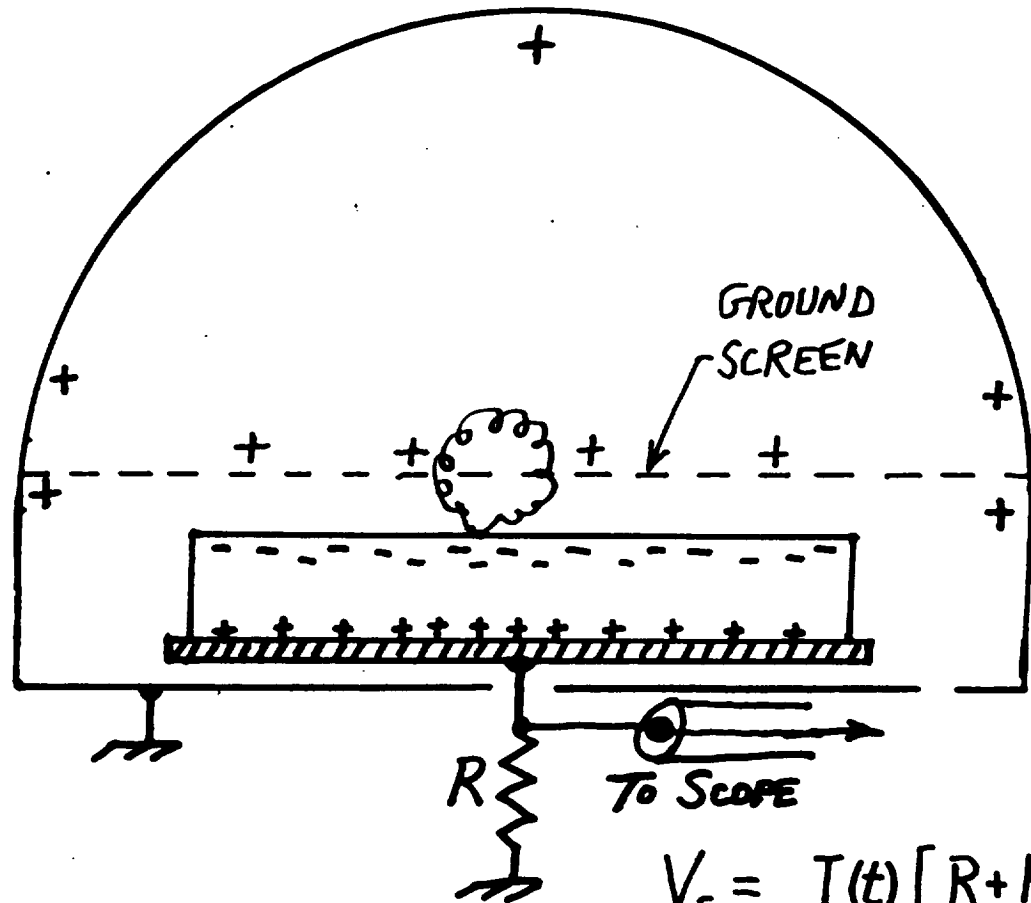
ANSWER: HOLES MOVE CLOSER TO
THE STUCK ELECTRONS,
NEGATIVE SCOPE TRACE.

WHAT CONTROLS $R_p(t)$?



PLASMA : DENSITY, TEMP, % IONIZED
DISTANCE TO WALL

EFFECT OF SMALL CHAMBER, CLOSE WALL



- BETTER FASTER PLASMA CONDUCTION
- SMALLER R_p -- LARGER $IR \Rightarrow$ SCOPE

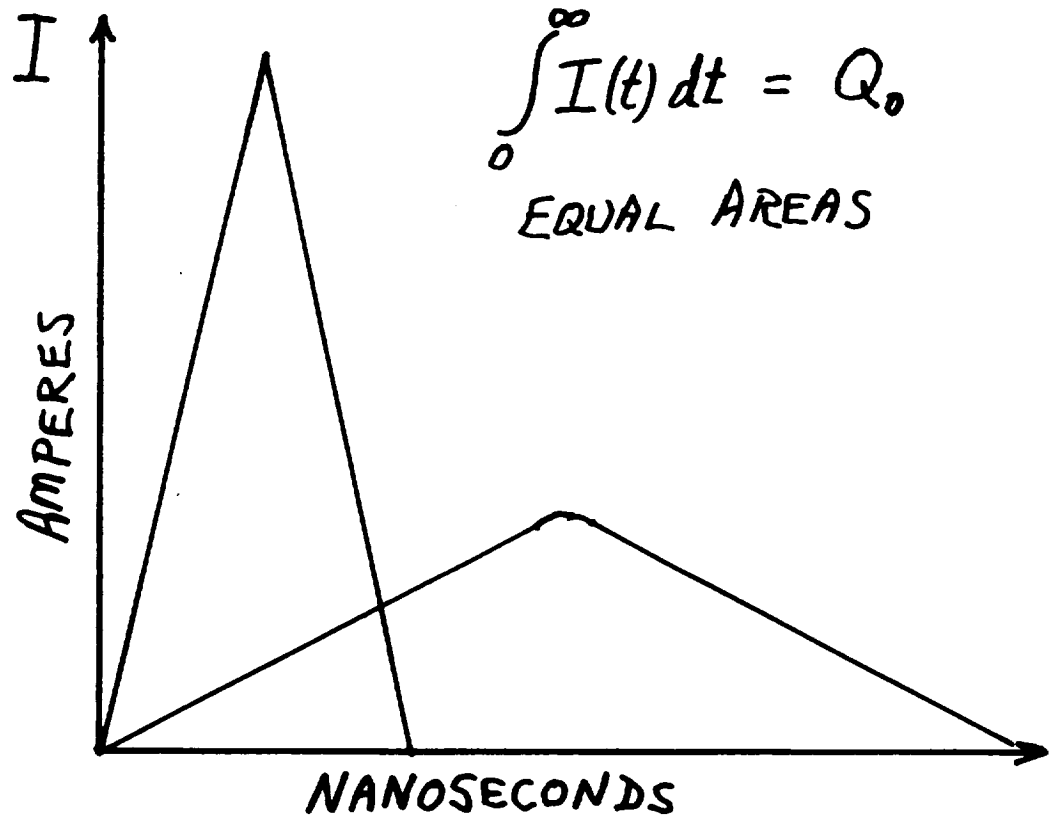
A SCALING LAW

LARGE VACUUM CHAMBERS > 30 CM

LARGE R_p and LOW I (SLEW RATE)

SMALL VACUUM CHAMBERS << 30 CM

MODERATE R_p and MODERATE I (SLEW RATE)

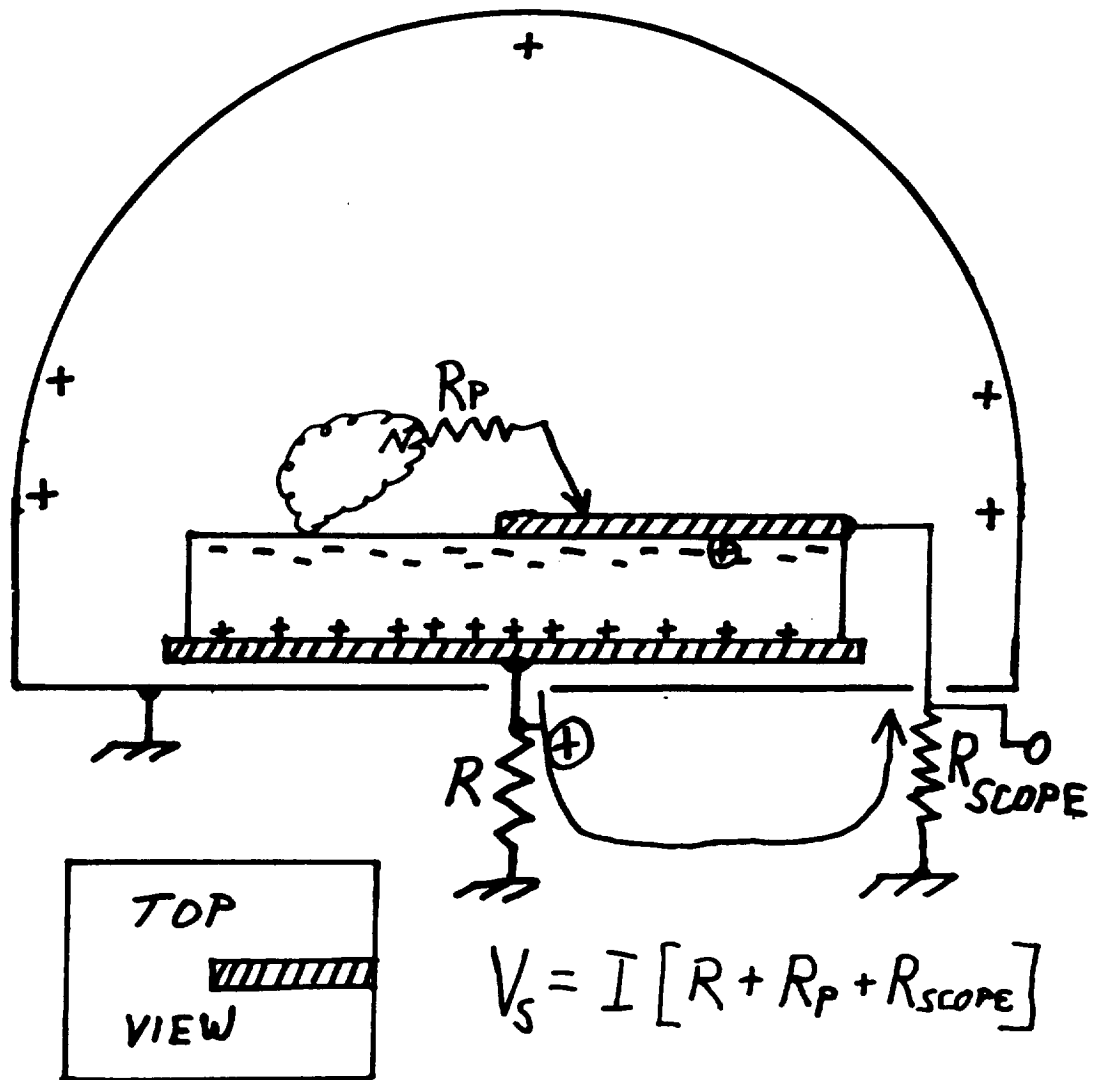


THUS, THE GEOMETRY OF VACUUM AND
ELECTRODES IS IMPORTANT

**CONSIDER A TRACE ON THE TOP OF THE
INSULATOR. THIS IS SIMILAR TO BRINGING
SOME OF THE GROUNDED SCREEN DOWN ONTO
THE INSULATOR.**

**SO, ONE MIGHT GUESS THAT WE HAVE A
MODERATE SLEW RATE AS IN THE SMALL
VACUUM CHAMBERS.**

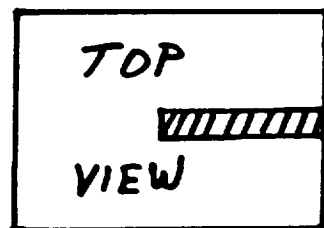
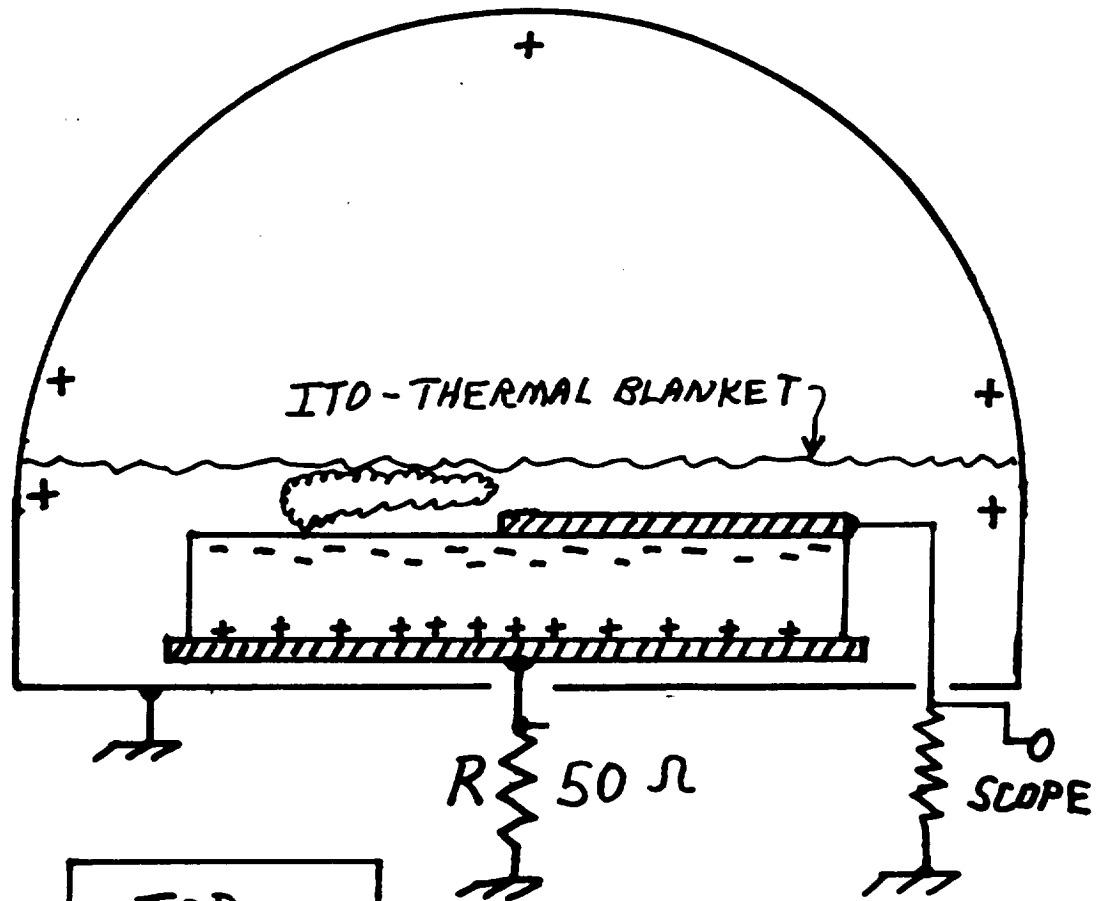
**WE DO. BUT THE PULSE VOLTAGE RELATIVE TO
CHASSIS DEPENDS ON WHICH RESISTOR WE
MONITOR.**



**THE WORST GEOMETRY
THE HIGHEST SLEW RATE
THE HIGHEST CURRENT**

**PLACE AN INSULATING SHEET ABOVE THE
CIRCUIT BOARD TO CONFINE THE PLASMA. THIS
CONSTRAINS ALL THE PLASMA TO CONDUCT TO
THE TRACE.**

WORSE CASE TO DATE

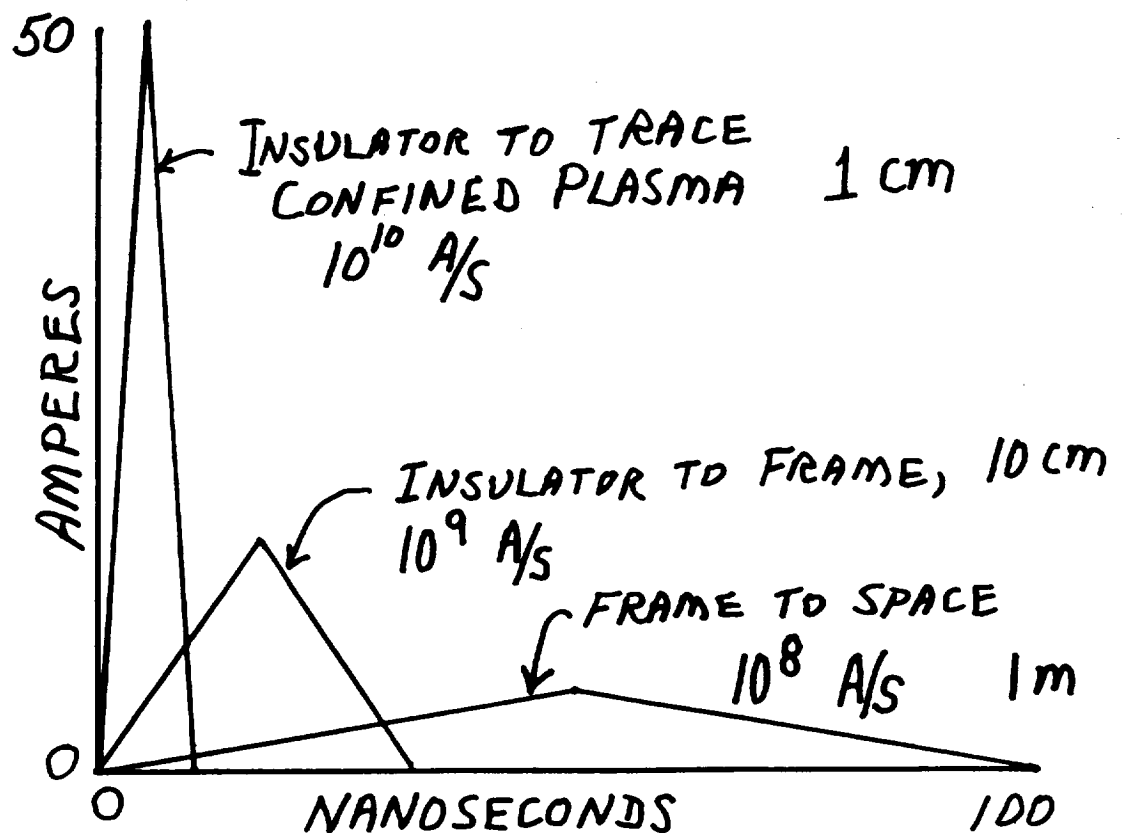


$$I_p R = 2000 V_p$$

ON TYPICAL CIRCUIT

PULSE SCALING LAW

$$\int_0^{\infty} I(t) dt = Q_0 \quad (\text{moving holes})$$



SUMMARY

Most Data is for 5 to 15 kV Charged Surfaces.
Lower E Field Implies Lower Slew Rate.

Preliminary Data Based on Partial Review of Literature

WORST CASE SLEW RATES ARE:

Frame to Space: 10^8 A/sec

Insulator to Frame: 10^9 A/sec

Insulator to Trace: 10^{10} A/sec

THE RULE:

- 1) Estimate Q , total "hole" charge that moves.
- 2) Choose slew rate based on geometry.
- 3) At first, assume sensitive circuit R is small.
- 4) Draw triangle function $I(t)$ from slew rate.
- 5) Integrate and Normalize $I(t)$ to equal Q .
- 6) Evaluate: **Does $R \cdot I(t)$ threaten the circuit?**
- 7) Estimate $I(t)$ with real R , is this threatening?